A Gamma-Ray Monte Carlo Study of the Clumpy Debris of SN1987A

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ABSTRACT

We have performed Monte Carlo calculations of gamma-ray transport in models of the clumpy debris cloud of the LMC supernova, SN1987A, to study the influence of composition mixing and heterogeneity on its emergent gamma-ray and X-ray fluxes. In particular, we have focused on the problematic Ginga band (16 – 28 keV) flux at day 600, whose measured value was an order of magnitude higher than predicted by previous theory. We find that the hydrogen of the envelope could not have been intimately mixed with the heavy elements of the core and that the hydrogen/helium volume filling factor interior to 4000 km s^{-1} must have been large ($\geq$ 40%). Furthermore, we demonstrate that that one can not mimic the effects of clumping by artificially decreasing the photoelectric cross sections by some factor. A physical separation of the Compton scattering region and the regions occupied by the high-Z elements is required. The 600-day models that best fit both the line data at 847 keV and 1238 keV and the measured Ginga band fluxes suggest that as much as 50% of the explosively produced ^{56}Ni stayed interior to 1000 km s^{-1} and 2 $M_{\odot}$. The ^{56}Ni may have been more centrally-concentrated than in the benchmark models. ^{56}Ni filling factors greater than 60% are not preferred, since such models are too good at absorbing photons below 100 keV. Furthermore, a total envelope mass between 10 $M_{\odot}$ and 15 $M_{\odot}$ is favored.

1. Introduction

One of the major highlights of the campaign to observe the recent LMC supernova, SN1987A, was its early detection in gamma-ray lines and hard X-rays (Matz *et al.* 1988; Sandie *et al.* 1988; Cook *et al.* 1988; Rester *et al.* 1989; Mahoney *et al.* 1988; Gehrels, Leventhal, & MacCallum 1988; Sunyaev *et al.* 1988; Ubertini *et al.* 1988; Teegarden *et al.* 1989). An international effort involving satellites (NASA's Solar Maximum Mission and the Compton Gamma-Ray Observatory, ROENTGEN on Russia's MIR-KVANT) and balloons (*e.g.,* Tueller *et al.* 1990) successfully detected the 847, 1238, 1771, and 2598 keV gamma-ray lines of the (^{56}Ni$\rightarrow$)^{56}Co$\rightarrow$^{56}Fe decay sequence and their Comptonized continuum down to a few tens of keV. In addition, the GRO detected at day 1620 the 122 keV/136 keV blend plus continuum from the decay of (^{57}Ni$\rightarrow$)^{57}Co to ^{57}Fe, long predicted to be explosively produced with the more abundant ^{56}Ni (Kurfess *et al.* 1992; Clayton *et al.* 1969; Clayton *et al.* 1974; Colgate & McKee 1969). That such radioactivities were strongly indicated by the light curves and optical/IR spectra of SN1987A and other supernovae in no way detracts from their direct detection via gamma-ray spectroscopy.

However, as SN1987A evolved, theorists were forced by the shape of its UVOIR light curve and the early emergence of the 847 and 1238 keV lines (starting day 180) and continuum (starting day 130) from ^{56}Co decay to revise their assumptions about the spatial distribution of the ^{56}Co in the debris (Woosley *et al.* 1987; Gehrels, MacCallum, & Leventhal 1987; Chan & Lingenfelter 1987; Ebisuzaki & Shibazaki 1988; McCray, Shull, & Sutherland 1987). A central point source of ^{56}Ni would have been visible only after 400–600 days. Mixing of ^{56}Ni out beyond the Hydrogen/Helium interface to velocities of $\sim$4000 km s^{-1} and interior model masses greater than 10 M$_\odot$ was invoked to keep pace with SN1987A's actual behavior (Pinto & Woosley 1988; Nomoto *et al.* 1988). This implied that there had been severe hydrodynamic instabilities during the outward progress of the

supernova shock wave that mixed ^{56}Ni into the stellar envelope from its birth at $\sim$500 km s^{-1} and $\lesssim$1 M$_\odot$ in the deep interior of the debris (Arnett, Müller, & Fryxell 1989; Herant & Benz 1992). Nevertheless, multi-dimensional simulations of the Rayleigh-Taylor mixing instabilities have failed to date to reproduce the extent of the ^{56}Ni penetration and the detailed character of the clumps. Instabilities during the explosion itself are suspected to be necessary, but this has yet to be demonstrated (Herant & Benz 1992; Burrows & Fryxell 1992; Burrows, Hayes, & Fryxell 1994).

The models such as "10HMM" (Pinto & Woosley 1988) and "sn14e1" and "sn11e1" (Nomoto *et al.* 1988) that were altered to fit the optical and hard photon data had spherical element distributions determined empirically, not physically. The isotopes of the pre-supernova progenitor and those produced explosively were all mixed on microscopic scales and no attempt was made to model the heterogeneity of the ejecta. Such heterogeneity is, however, indicated by the ragged line profiles observed in the optical and infrared (Jennings *et al.* 1993; Hanuschik *et al.* 1993; Spyromilio, Meikle, & Allen 1990; Cannon & Stathakis 1988) and at some level in the gamma-ray (Tueller *et al.* 1990). A reluctance to tinker further with models that seemed to fit the gross properties of SN1987A's UVOIR, gamma-ray, and X-ray evolution is understandable, particularly since the theoretical calculations of the Rayleigh-Taylor instabilities are even now in an embryonic stage.

However, from day 130 through day 650 the Japanese satellite **Ginga** detected X-rays from SN1987A in the 16–28 keV band (Tanaka 1988a; b; c; 1991) that have never been successfully fit after day 520, and have never been fit after day 400 without excessive artifice. At day 600, the discrepancy at 16–28 keV (hereafter, the "Ginga band") between the predictions of models that fit the gamma-ray *lines* to within a factor of two is between a factor of 5 and 25. The Ginga photons originate from $\sim$5–20 Compton down-scatterings of gamma-ray lines from ^{56}Co decay, ^{57}Co decay, and positron annihilation (McCray 1993).

To emerge at these relatively low energies, the hard photons must not only scatter many times before escaping, but must avoid being absorbed photoelectrically by the multitude of heavy elements, in particular those of the iron group. Since the emergent Ginga photons must have followed a tortuous path, they are ideal probes of the entire structure and composition of the supernova debris cloud. Even better than the nuclear lines, the Ginga photons provide a global "X-ray" that is diagnostic of the element yields, distributions, and mixing. It is this great investigative leverage of the Ginga band and the failure to date to explain the late-time Ginga flux that has motivated this paper. Here, we distill the results of about one hundred gamma-ray Monte Carlo calculations we have recently performed in clumpy, *heterogeneous* models of SN1987A. We focus on the Ginga flux at day 600 to investigate the degree of mixing of light (hydrogen and helium) and heavy (Ni−Co−Fe, Si, etc.) elements, their volume filling factors, and their radial distributions, using as starting points the models sn14e1 and 10HMM.

Kumagai *et al.* (1989) attempted to fit the late Ginga data with a spherical model by artificially cutting the photoelectric cross-sections down by a factor of 9. This was done to mimic the self-shielding effect of dense clumps of intermediate to heavy nuclei. However, their ansatz failed beyond day 520 and they resorted to a buried pulsar, not now indicated (Suntzeff *et al.* 1991), to account for the last data points. The *et al.* (1990) explored spherical models with different velocities and masses, but fared no better than Kumagai *et al.* (1989) beyond day 520. The *et al.* (1993) used a cloud model inspired by Bowyer & Field (1969), but though their paper contained many interesting suggestions, they too failed to explain the late Ginga data. The essential problem, discussed by McCray (1993), is that the Ginga photons originate in regions of freshly-synthesized iron-group elements (with total mass ~ 0.07 $M_\odot$), but must down-scatter in regions composed predominantly of hydrogen and helium (≥ 5 $M_\odot$). This implies that iron and hydrogen in SN1987A are physically segregated, and are not intimately mixed, as was assumed in models 10HMM, sn14e1, and

sn11e1. Otherwise, if the photons were to scatter in hydrogen significantly contaminated by heavy elements, the probability would be high that they would be absorbed before reaching the energies of the Ginga band. The optical/IR data obtained from SN1987A say little about the degree of segregation of the hydrogen/helium, the iron-peak, and the intermediate-mass elements. However, the gamma-ray Monte Carlo simulations we present in this paper demonstrate and quantify this effect.

Furthermore, and as reviewed in §II, while there is optical evidence for hydrogen in large clumps and at low velocities and radii (Hanuschik *et al.* 1993), these data do not constrain the total mass of hydrogen nor its volume filling factor. In addition, while oxygen is seen in many small clumps (Cannon & Stathakis 1988) and its total mass may reach 1.5 $M_\odot$ (Chugai 1994), its volume filling factor, now estimated at $\sim$10%, is uncertain by more than a factor of five. In fact, it is only the product of the oxygen mass and its filling factor that is constrained by the optical data (McCray 1993). While there is some evidence for radioactive cobalt at small radii (Hanuschik *et al.* 1993) and the iron-peak elements are known to extend to 4000 km s^{-1}, their radial *distribution* is not well-known. Finally, Li, McCray, & Sunyaev (1993) suggest on the basis of infrared line data that the iron-peak elements have a disproportionately high volume filling factor (10% – 90%?). However, only their lower limit is firm. The Ginga data at day 600 can be used in conjunction with our new gamma-ray transport calculations to address all these issues. In particular, a comparison between these data and the results of the Monte Carlo calculations allows us to constrain the hydrogen/helium mass, the hydrogen and iron filling factors, and the radial distribution of the $A = 56$ elements.

2. Idealized Models of the Heterogeneous Structure of the SN1987A Ejecta

Optical and infrared data have already been used to estimate the radial distributions and volume filling factors of the debris (McCray 1993). We were guided by these data in manufacturing our ejecta models and in posing the questions we wanted our study to address. A synopsis of what they suggest can provide the context of our studies of SN1987A heterogeneity. Ultimately, we want to determine whether a consistent picture can be constructed and what new and useful insights can be gained by focusing on the Ginga band near day 600.

Hanuschik *et al.* (1993) have analyzed $H\alpha$ data from day 115 to day 673 and find in the jagged line profiles evidence for ~ 5 large "bumps" in the radial velocity range -2000 km s^{-1}$< v <$ 1300 km s^{-1}, with widths near 500 km s^{-1}. They say that some hydrogen is at quite low velocities, significantly lower than the minimum velocity ($\sim$ 3000 km s^{-1}) hydrogen would have had if the nested onion-skin structure of the progenitor had not been violated. They see no evidence of intact shells and see peaked profiles that can also imply deep penetration. They think they see "extra emission" in the bumps, symptomatic of proximity to some of the radioactive source (^{56}Co) of Compton electrons and gamma rays. Hanuschik *et al.* can not say much about the H/He volume filling factor or the total hydrogen mass and are unable to say anything about the possible existence of "fingers."

Cannon & Stathakis (1988) observe at high spectral resolution ($\frac{\lambda}{\Delta\lambda} \sim 30000$) the 6300, 6363Å [OI] doublet and identify many (they say ~ 50) small-scale oxygen clumps down to widths of $\Delta v \sim 60$ km s^{-1}. Chugai (1994) interprets these same data with a statistical model of ~ 2000 clumps of "oxygen" with an average clump "radius" of 60 km s^{-1}, a clump mass of $\sim 10^{-3}$ M$_\odot$, a total mass of 1.2–1.5 M$_\odot$, and a volume filling factor of 10%. His model puts all the emitting oxygen at radial velocities below $\sim$1700 km s^{-1} (at half the radius of the outer "nickel" bullets). Wampler (1994) lends indirect support to the larger

oxygen clump number with a super-resolution ($\frac{\lambda}{\Delta\lambda} \sim 10^6$) [OI] spectrum in which clumpy structure is seen below $\Delta v \sim 60$ km s^{-1}. No Fourier or wavelet analysis of these data has been circulated.

Li, McCray, & Sunyaev (1993) have analyzed the nickel, cobalt, and iron data in the near- and mid-infrared and have constructed a model for the iron-peak spatial distribution. They see ∼60–100 clumps of Ni-Co-Fe below 2500 km s^{-1}, with a volume filling factor greater than 10%. They infer a "frothy" structure of low-density "iron" surrounded by higher density filaments of H, He, and other elements. The evidence for high density hydrogen and helium is weak, but the high "iron" filling factor is consistent with the predicted expansion of the radioactive nickel ("nickel bubble") and cobalt during the first weeks of explosion (Basko, 1994). (Note that the freshly synthesized iron-peak nuclei comprise only about 1% of the ejectum mass.)

Clearly, an infinite number of parameters could characterize the heterogeneity of clumpy supernova debris. It might at first glance seem natural to use the published (Arnett, Müller, & Fryxell 1989; Herant & Benz 1992) two-dimensional hydrodynamic simulations of SN1987A's envelope for our Monte Carlo calculations. However, since ^{56}Ni penetrates to only 2000 km s^{-1} in those simulations and they do not credibly include the effects of gamma-ray and heat leakage at late times, their use was not advisable. Without a specific model to falsify, we were forced to construct "artificial" debris clouds with gross properties that were still consistent with most of what was known. The major constraints on these models were the given isotope masses of the original progenitor models (10HMM or sn14e1), the observed velocity range of ^{56}Ni, and the homology of the velocity field. To make this project manageable, we focused on a set of specific synthetic structures and element distributions (with variations) that we felt would bracket the range of realistic ejecta. Our models spanned a far broader range of density contrasts and clump size distributions

than are to be found in the two-dimensional hydrodynamic simulations of SN1987A. We also looked at the effect of various degrees of central concentration of both iron-peak elements (hereafter, composition 2) and intermediate mass elements ($2 < Z < 26$, hereafter, composition 0). Identifying the matter of the H/He zones of the original stellar models with composition 1, we distributed the three compositions in two or three phases. (For the two-phase models, composition 0 included helium and composition 1 was pure hydrogen.) A phase was either a denser radial finger (various total finger volumes, and hence densities, were used) or the interstitial space between the fingers. The two-phase calculations involved one set of denser fingers surrounded by lower-density interstitial gas and the three-phase calculations involved two set of fingers of different compositions surrounded by an interstitial phase of a third composition. In the two-phase calculations, the fingers or the space between the fingers could be made of different mixtures of compositions (composition 2 with composition 1, composition 2 with composition 0, etc.). Breaking the ejecta thusly into phases was suggested by the "onion skin" structure of supernova progenitors and the hydrodynamic simulations of Arnett, Müller, & Fryxell 1989 and Herant & Benz 1992.

A set of planes and cones were introduced to partition the initial spherical model and define the finger regions. The planes are parallel to and pass through a single axis of the star and are equally spaced in the meridional angle, θ, around this axis. This line is also the axis of the cones. The double-sheeted cones share a common vertex at the center of the star. The polar angles ϕ of the cones are chosen to give equal volumes between successive cones, including the interior of the polar-most cone and between the lowest cone and the equator. Any plane through the axis is a plane of reflection symmetry, as is the equator. We label the angular division by the number of planes N_θ and cones N_ϕ. There are $2N_\theta \times 2(N_\phi + 1)$ equal volume angular elements. Each element is assigned composition 0, 1, or 2 (or some mixture in the two-phase model); these assignments are the same for each radial shell. Each composition has a single density within a shell. When the matter

of a composition is contained in a sparse set of isolated angular elements, dense fingers are formed. It should be kept in mind when considering these models that the detailed shape of a Rayleigh-Taylor plume (*i.e.,* whether it is square or rounded) can not be discerned in emergent hard spectra. Since diffusing photons quickly lose their orientation as they scatter, the output of a transport calculation depends more on the integral, average, and global properties of the debris cloud than on its details. Models with a variety of "tilings," for example with and without channels to the surface, give roughly the same answers for the same global parameters (*i.e.*, filling factors, nickel mass, density contrasts, degree of central concentration). It is in this spirit that we constructed the models we did. Furthermore, calculations with this relatively simple geometry are more efficient than those with geometries that are more elaborate. With these models we have spanned in a systematic way a very broad range of volume filling factors, density contrasts, and nickel distributions.

Figure 1 depicts a typical two-phase finger pattern and Figure 2 shows a three-phase geometry. We ran a large number of models to investigate various element mixtures, finger densities, finger numbers, and the angular distribution of fingers. The three-phase models were parametrized by the volume filling factors of the compositions, which are determined by the finger patterns. These filling factors, together with the starting spherical model, the fixed element masses, and the radial extent of the fingers implicitly give the finger density contrasts. Finger contrast ratios from one to almost 600 were studied. In all, the gamma transport in more than sixty models at day 600 was calculated. The almost thirty models in Table 1 summarize this more extensive list. (We also did a total of more than fifty Monte Carlo calculations at days 200, 400, 500, and 700.)

We used both a coarse ($N_\theta \times N_\phi = 8 \times 8$) and a fine ($N_\theta \times N_\phi = 24 \times 24$) angular division in both the two- and three-phase models. Tables 2a and 2b show examples of

the angular assignment patterns. In some cases, a three-phase template was created by inserting fingers of a third composition at random positions in a two-phase pattern. Table 1 lists the model names, but not the logic of the character strings that define them. The first field (each field is separated by a period) indicates the original SN1987A model used (either sn14 (sn14e1) or hmm (10HMM)). The letters after the original model designator in the first field indicate special radial composition distributions. The letter "e" means that all the composition fractions were constant from the center to 3000 km s^{-1}, "f" means that the composition fractions were flat at their original central SN1987A model values, and "c" means that the ^{56}Ni distribution was constant out to 7 $M_\odot$. The latter represents a significant central concentration of ^{56}Ni, since it has been inferred (and the original models assume) that some nickel bullets penetrated to at least 12 $M_\odot$. When no letter is given, or unless otherwise indicated, the original (default) model radial element distributions should be assumed. The next field (always .600 for the models considered here) identifies the epoch (in days) of SN1987A. The digits in the last field indicate the angular division (e.g. 8×8, 24×24). The terminal letter identifies the combination of filling factors, number of phases, and additional special characteristics for that specific model. Table 3 depicts the meanings of these terminal letter designators for the models listed in Table 1 and should be considered an important footnote to it.

3. The Monte Carlo Code

To calculate hard photon transport in spherical supernovae, we had formerly constructed a Monte Carlo code based on the variance-reduction algorithm of Pozdnyakov, Sobol, & Sunyaev (1983) (The, Burrows, & Bussard 1990). Rather than redesign that

code to handle arbitrary geometries, we decided to employ the MCNP[†] code developed and maintained by the Transport Methods Group of Los Alamos National Laboratory (Briesmeister 1986; Forester *et al.* 1990). MCNP is a general-purpose Monte Carlo code for calculating the time-dependent continuous energy transport of neutrons, photons, and/or electrons in three-dimensional geometries. The code has been successfully compared against numerous benchmark problems and is subject to formalized quality assurance procedures. MCNP is used for many applications, including nuclear oil well logging, medical imaging and radiotherapy, nuclear reactors (both fission and fusion), space science, nuclear safeguards, personnel dosimetry, detector design and analysis, and radiation shielding. We have used MCNP in previous studies of gamma-rays from Type Ia supernovae (Burrows, Shankar, & Van Riper 1991) and found excellent agreement with the results of other Type Ia calculations. (MCNP does not account for Doppler shifts in photon creation and interactions and thus does not give realistic line shapes; the flux in a line and the continuum spectrum are unaffected by this neglect.) The photon physics model includes Compton scattering, photoelectric absorption, fluorescence, and the Auger effect. Although MCNP is rich in variance-reduction techniques, we used only importance splitting based on radius. For our calculations, a continuous (rather than multigroup) energy representation was used for the photons.

MCNP can follow the transport of secondary Compton electrons and their bremsstrahlung photons. Bremsstrahlung had originally seemed to us a good source of Ginga photons, but we later discovered that above 15 keV, bremsstrahlung does not contribute a competitive fraction of the flux. Compton photons still dominate down to the Ginga band. Nevertheless, most of the calculations we report here were done with

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the bremsstrahlung yield included. The bremsstrahlung is calculated in the "thick-target" model, where the radiation distance of the electron is assumed to be much less than other scales and the spatial transport of the electron away from the emission site is neglected. A similar bremsstrahlung treatment was used by Clayton & The (1991).

As in our original spherical supernova studies, the ^{57}Ni and ^{56}Ni decay schemes, energies and branching ratios were taken from Browne *et al.* (1978) and it was assumed that all positrons form positronium before annihilating (Bussard, Ramaty, & Drachman 1979). MCNP comes with its own photoelectric cross section library. Between 10^5 and 5×10^5 decays were followed per run, and for each run a statistical error estimate was made. The Ginga fluxes that we quote have a statistical error of between 0.5 and 3 percent.

4. The Ginga Band Model Fluxes at Day 600 and Their Interpretation

Figure 3 shows the Ginga band data accumulated during the SN1987A campaign (Tanaka 1988a; b; c; 1989). Superposed are the 600-day predictions of a few representative models from Table 1. As the figure shows, the 16–28 keV Ginga band flux was measured to be $4 \pm 2 \times 10^{-4}$ photons cm^{-2}s^{-1} between days 550 and 650. The fact that the Ginga fluxes of the spherical models sn14.600.sph and hmm.600.sph at day 600 (Table 1) are only 6.96×10^{-5} cm^{-2}s^{-1} and 1.61×10^{-5} cm^{-2}s^{-1}, respectively, is the "Ginga Problem." The former is lower by a factor of ~ 6; the latter by a factor of ~ 25. The sn14e1-derived model has four times the flux of the 10HMM-derived model predominantly because sn14e1 has a larger mass of hydrogen on which to Compton-scatter (5.6 $M_\odot$ versus 4.5 $M_\odot$), has a larger fraction of its ^{56}Ni near the center, and has less than half the burden of silicon, sulfur, argon, and calcium isotopes (respectable photoelectric absorbers). All these factors have a bearing on what fits.

Table 1 (with reference to Table 3) contains the major results of our Monte Carlo simulations and should be scrutinized closely. We summarize here what it says. By comparing sn14.600.2424h′ with sn14.600.2424k we can see the drastic effect of mixing hydrogen with the iron-peak nuclei. The "h′" model flux is *six* times lower. A similar effect of intimate mixing is seen in model sn14.600.2424g. In fact, none of the models that mixed compositions 2 and 1 came anywhere near the data. From this, we conclude that most of the ^{56}Ni and H/He could not have mixed and that these compositions *must* be separated in SN1987A.

A comparison of models hmm.600.88h and hmm.600.2424h shows that a finer finger division with larger density contrasts yields a larger Ginga flux, all else being equal. The "2424" model has more than twice the Ginga flux of the "88" model. This is as one may have anticipated and is a universal feature of the models in Table 1. The generically small effect of including the bremsstrahlung of Compton electrons can be discerned by comparing models hmm.600.88h and hmm.600.88hnob. Bremsstrahlung increases the Ginga band flux at day 600 by no more than 2–3%. The effect of clumping all the way to the surface (instead of to 4000–5000 km s^{-1}) can be seen by comparing models sn14.600.88t and sn14.600.88r. Having channels to the surface (not expected or indicated in the early optical data) increases the escape probability of the Ginga photons by only 7–10%. At day 600, the outer envelope is generally transparent and it is in the inner zones interior to 3000 km s^{-1} that the Compton X-rays are created (The, Burrows, & Bussard 1990).

We now turn to the effect of volume filling factors (f) on the emergent Ginga flux. (Refer as needed to Tables 1 and 3.) Models "t" have $f(0) = 0.819$, $f(1) = 0.083$ and $f(2) = 0.097$. Most of the volume in the clumped region is filled with low-density intermediate Z elements. Models "u" and "v" have $f(1) = 0.72$ and 0.79, respectively, and each has $f(0) = 0.097$ (only ∼10%). Otherwise, they are similar. Comparing sn14.600.88t and sn14e.600.88t with

models sn14.600.88u, sn14.600.88v, sn14e.600.88u, and sn14e.600.88v shows the dramatic importance of a large H/He volume filling factor. It is hard with a small $f(1)$ ($< 20\%$) to fit the Ginga data at day 600. All the models with the highest fluxes have large $f(1)$ ($> 40\%$). As a comparison of sn14.600.88s ($f(2) = 0.097$) with sn14.600.88p ($f(2) = 0.417$) shows, it is more nearly the *sum* of the composition 0 and composition 2 volume filling factors that is constrained. This is also implied by the high flux of model sn14.600.2424k, for which all $Z > 2$ elements are contained in very dense fingers. This indicates that most of the H/He (composition 1) is not contaminated by the strong photoelectric absorbers of compositions 0 and 2, that a high $f(1)$ is preferred, and that $f(0)$ and $f(2)$ are not individually determined by the Ginga data.

One tentative conclusion of this work is that despite the enhancements in the Ginga flux from the modifications described above, central concentration of the iron peak elements beyond that provided by the fiducial SN1987A models can further improve the fits. Placing the "nickel" deeper inside the debris increases the Compton opacity and allows more Compton photons to be created. At day 600, nickel in the outer envelope creates gamma line photons that escape uselessly to infinity. This effect is amplified in the "e" and "f" series calculations that put too much ^{56}Ni, ^{56}Co, and ^{56}Fe at large radii. We see the effect of central concentration by comparing model sn14c.600.2424s with model sn14.600.2424s or model sn14c.600.88u with model sn14.600.88u. The "c" series has 50% to 70% higher Ginga fluxes.

Importantly, as indicated in the full spectra depicted in Figures 4 and 5, central concentration tends to decrease the emergent *line* fluxes in the MeV range. The theoretical models have generally overestimated the late (>300d) line fluxes (The, Burrows, & Bussard 1990 and their Figures 3 and 4). This mismatch is only about a factor of two and, given the low S/N ratio of gamma line data, was not considered a major problem. Our

calculations indicate that while concentrating more "nickel" in the center may contribute to the solution of the Ginga Problem, it can also resolve the milder 847 and 1238 keV line flux discrepancies. In addition, concentrating the nickel much further than we have done in this study cuts the line fluxes at day 614 by *too* much (Tueller *et al.* 1990). Thus, and very approximately, we have both lower and upper limits on the nickel radial distribution. Centrally-concentrated model sn14c.600.2424s fits all the data to within 1σ. This implies that while some of the explosively produced ^{56}Ni was obviously flung to high radii, velocities, and interior masses, a large portion of it may not have been. This result may be of importance in understanding the hydrodynamic instabilities that violated the shell structure of the progenitor of SN1987A. The two-phase model, sn14.600.2424k, yields the highest Ginga band flux of the set depicted in Table 1, but does so with a density ratio between the $Z > 2$ and the hydrogen/helium "phases" of close to 600. This ratio is perhaps too extreme to be physical, but its success in fitting the Ginga band at day 600 should not be ignored.

A final result of our series of Monte Carlo calculations is the recognition that the debris of SN1987A had to have at least 5 $M_{\odot}$ and preferably closer to 10 $M_{\odot}$ of hydrogen and helium to give any Ginga flux at all at day 600. In fact, a model with only 3 $M_{\odot}$ of hydrogen would miss the observed 600-day Ginga band flux by a factor of as much as one hundred. This means that the mere detection from SN1987A at day 600 of Ginga band photons implies that its debris mass had to be above $\sim$7 $M_{\odot}$. This result is consistent with the large sn14e1 and 10HMM model envelope masses.

5. Conclusions

Since the photons that eventually emerge from SN1987A in the Ginga band have scattered numerous times and have lost their orientation, artificial debris models with a range of filling factors, average density contrasts, and integral properties can be used in conjuction with the observed Ginga band photons to constrain these global properties. The detection by Ginga on day 600 of photons in the 16–28 keV band at the substantial level published implies that in SN1987A the hydrogen could not have been intimately mixed with either the iron-peak elements or the elements with Z's between 2 and 26. In addition, the hydrogen/helium volume filling factor interior to 4000 km s^{-1} must have been large ($\gtrsim$ 40%). Furthermore, perhaps as much as 50% of the explosively produced ^{56}Ni stayed interior to 1000 km s^{-1} and 2 M$_\odot$; the ^{56}Ni may be more centrally concentrated than in the published benchmark SN1987A models. We have demonstrated that one can not mimic the effects of clumping by simply decreasing the effective photoelectric cross sections by some factor (*cf.* Kumagai *et al.* 1989). A physical segregation of the Compton scattering region from the regions of the "photoelectric" elements is required. Our best heterogeneous models not only solve the Ginga Problem at day 600, but improve the fits of the 847 and 1238 keV line data with theory. A large ^{56}Ni filling factor ($f(2) > 60\%$) is disfavored, since such models are too good at absorbing photons below 100 keV (*cf.* Li, McCray, & Sunyaev 1993). In fact, it is the sum of the filling factors for all of the $Z > 2$ elements that is probed by the Ginga data and a sum value less than 50% is suggested, though a model with $f(1) = 50\%$ and $f(0) + f(2) = 50\%$ can be accommodated by the data. No model with a total envelope mass less than 5 M$_\odot$ can possibly fit all the line and Ginga band data between days 300 and 650. A total envelope mass between 10 M$_\odot$ and 15 M$_\odot$ is favored.

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Figure Captions

Figure 1: Two-Phase pattern. Three-dimensional representation of the two-phase pattern pat_88_10. The fingers are shaded and the region between the fingers is transparent. The innermost zone is opaque. The outermost zone contained within the fingers is shown in a darker shade as an aid to the eye. The fingers encompass 10% of the volume.

Figure 2: Three-Phase pattern. Three-dimensional representation of the three-phase patterns pat_2424_tw and pat_2424_tx. In pattern pat_2424_tw, the compact fingers containing composition 2 are dark grey, composition 0 is light grey, and composition 1 is transparent. For pat_2424_tx, the composition assignments are 0 in the dark grey, 2 in light grey, and composition 1 is again transparent. The outermost radial zone of the light grey volume has been made transparent to permit better recognition of the dark fingers. The dark fingers represent 0.83% of the volume, the light regions 43.7% of the volume, and the transparent composition 1 regions 55.5% of the volume.

Figure 3: A plot of the measured flux in the Ginga band (16 - 28 keV) versus time. The error bars are 1-sigma error bars. The solid line is the theoretical prediction for the 10HMM model of Pinto & Woosley (1988) and the dashed line is the theoretical prediction for the sn14e1 model of Nomoto *et al.* (1988), both as calculated by The *et al.* (1990). This paper focuses on the discrepancy at 600 days. The symbols at day 600 are representative results from our multi-dimensional Monte Carlo calculations. The models in order of increasing flux at 600 days are hmm.600.sph (B), sn14.600.2424h′ (J), sn14.600.sph (A), sn14.600.88t (S), sn14.600.88p (M), sn14.600.2424s (R), sn14c.600.2424s (W), and sn14.600.2424k (L). The capital letters used to identify the models here are the same letters used in the listing on Table 1.

Figure 4: A superposition of the spectra (in photons cm^{-2}s^{-1}keV^{-1}) from 10 keV to 4 MeV at day 600 for models hmm.600.sph (B), sn14.600.2424h′ (J), sn14.600.2424g (K), sn14.600.sph (A), sn14.600.2424s (R), and sn14.600.2424k (L). The spikes are the lines and their heights are the line fluxes in photons/$[cm^2 \cdot s]$. The capital letters used to identify the curves here are the same letters used in the listing on Table 1.

Figure 5: Same as Figure 4, but for models sn14e.600.88v (V), sn14.600.88t (S), sn14.600.88p (M), sn14.600.88v (P), and sn14c.600.2424s (W).

Table 1.

Model Name	Ginga Band Flux ($\#/cm^2 \cdot s$)
Spherical	
A. sn14.600.sph*	$\mathbf{6.96 \times 10^{-5}}$
B. hmm.600.sph**	$\mathbf{1.61 \times 10^{-5}}$
C. sn14e.600.sph	1.41×10^{-5}
D. sn14f.600.sph	1.21×10^{-5}
E. sn14c.600.sph	9.46×10^{-5}
Two-Phase	
F. sn14.600.88h	1.90×10^{-4}
G. hmm.600.88h	8.30×10^{-5}
H. hmm.600.88hnob***	8.14×10^{-5}
I. hmm.600.2424h	1.87×10^{-4}
J. sn14.600.2424h′	4.54×10^{-5}
K. sn14.600.2424g	5.51×10^{-5}
L. sn14.600.2424k	$\mathbf{2.60 \times 10^{-4}}$
Three-Phase	
M. sn14.600.88p	1.19×10^{-4}
N. hmm.600.88p	5.10×10^{-5}
O. sn14.600.88u	1.30×10^{-4}
P. sn14.600.88v	1.46×10^{-4}
Q. sn14.600.88s	1.16×10^{-4}
R. sn14.600.2424s	1.48×10^{-4}
S. sn14.600.88t	9.15×10^{-5}
T. sn14.600.88r	9.82×10^{-5}
U. sn14.600.88q	1.22×10^{-4}
Fractions Flat to 3000 km/s	
sn14e.600.88t	3.81×10^{-5}
sn14e.600.88u	7.60×10^{-5}
V. sn14e.600.88v	8.45×10^{-5}
Central, Non-Spherical	
W. sn14c.600.2424s	$\mathbf{2.49 \times 10^{-4}}$
X. sn14c.600.88t	1.56×10^{-4}
Y. sn14c.600.88u	1.95×10^{-4}
Z. sn14c.600.88v	2.08×10^{-4}

*sn14e1 default element distribution
**10HMM default element distribution
***nob: no bremsstrahlung

Table 2b.

pat_2424_tw

	$\phi \rightarrow$																									
θ	1	2	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
$\downarrow$	2	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0
	3	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0
	4	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0
	5	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0
	6	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0
	7	0	0	0	0	2	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0
	8	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1
	9	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1
	10	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1
	11	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1
	12	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1
	13	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	2	1	1	1	1	1	1
	16	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
	17	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
	18	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
	19	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
	20	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	21	0	0	0	0	0	0	0	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1
	22	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	23	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	24	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

2424s: $f(0) = 0.437$

$f(1) = 0.555$

$f(2) = 0.00833$

Table 2a.

	pat_88_10											pat_88_tw									
	$\phi \rightarrow$											$\phi \rightarrow$									
θ	1	F	i	i	i	i	i	i	i	i	θ	1	2	0	0	1	1	1	1	1	0
$\downarrow$	2	i	i	i	i	i	i	F	i	i	$\downarrow$	2	0	0	0	1	1	1	2	1	0
	3	i	i	i	i	i	i	i	F	i		3	1	1	0	0	0	1	1	2	0
	4	i	i	F	i	i	i	i	i	i		4	0	0	2	1	1	1	1	1	1
	5	i	i	i	i	i	i	i	F	i		5	0	0	0	0	0	1	1	2	1
	6	i	i	i	i	i	i	i	i	i		6	1	1	1	0	0	0	0	0	1
	7	i	i	F	i	i	i	i	i	i		7	0	0	2	0	0	1	1	1	1
	8	i	i	i	i	i	F	i	i	i		8	0	0	0	1	1	2	1	1	1
		f(finger)= 0.097(F)											$f(0) = 0.417$								
		f(interstitial)= 0.903(i)											$f(1) = 0.486$								
													$f(2) = 0.097$								

Table 3.

	Terminal Letter Model Designators				
e:	Flat compositions to 3000 km/s, conserving mass				
f:	Flat compositions at central Y_i, conserving mass				
c:	Centrally concentrated ^{56}Ni, out to only $7M_\odot$				
sph:	Spherical distribution of elements, no clumping or heterogeneity				
	Two-Phase				
88h:	H/He in fingers, $Z > 2$ between fingers, pat_88_10, finger volume fraction=0.097				
2424g:	Ni and H in space between fingers, finger volume fraction=0.03, pat_2424_30				
2424h:	H and He between fingers, $Z > 2$ in fingers, finger volume fraction=0.0083, pat_2424_100				
2424h′:	Ni and H in space between fingers, finger volume fraction=0.0083, pat_2424_100				
2424k:	All $Z > 2$ in fingers, H/He in between, pat_2424_100				
	Three-Phase				
Composition:	0	1	2		
	$f(26 > Z > 2)$	f(H/He)	f(Ni)	Pattern	Comments
88t:	0.819	0.083	0.097	pat_88_tw2	clumping to 5000 km/s
88u:	0.097	0.72	0.18	†	clumping to 5000 km/s
88r:	0.819	0.083	0.097	pat_88_tw2	clumping to surface
88v:	0.097	0.79	0.11	†	clumping to 5000 km/s
88p:	0.097	0.486	0.417	†	clumping to surface
88q:	0.417	0.486	0.097	pat_88_tw	clumping to surface
2424s:	0.44	0.56	0.0083	pat_2424_tw	clumping to 5000 km/s
88s:	0.417	0.486	0.097	pat_88_tw	clumping to 5000 km/s

† Started with a 2-phase pattern pat_88_10, and then third phase added at random.